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STATISTICAL MEASUREMENTS OF CONTACT CONDITIONS OF COMMERCIAL TRANSPORTS LANDING ON AIRPORTS AT AN ALTITUDE OF 5,300 FEET AND AT SEA LEVEL

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STATISTICAL MEASUREMENTS OF CONTACT CONDITIONS OF COMMERCIAL TRANSPORTS LANDING ON AIRPORTS AT AN ALTITUDE OF 5,300 FEET AND AT SEA LEVEL

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SUMMARY

An investigation has been made to determine the effect of altitude on the statistical landing contact conditions of commercial transports during routine daytime operations. A comparison is made between measurements of 170 landings at mile-high Stapleton Airfield, Denver, Colorado (altitude 5,303 feet) with a statistically homogeneous sample of 170 landings made at sea-level International Airport, San Francisco, California (altitude 11 feet).

The analysis indicated that the only fairly definite effect due to altitude was on the vertical velocity, which was to reduce the severity, on the average, for landings made at the higher altitude. The mean vertical velocity at the mile-high Stapleton Airfield was 0.92 ft/sec compared to the mean value of vertical velocity at San Francisco of 1.27 ft/sec. The airspeeds, expressed in percentage above the stalling speed, were virtually the same at both airports, with mean values of 24 percent and 25 percent above the stall for Denver and San Francisco, respectively. There were significant differences in the statistics of touchdown distances from the runway threshold, rolling velocities, and bank angles between the Denver and San Francisco landings. Evidence indicated that these differences may have been partially the result of the differences in wind velocity parallel to the runway at the two airports. For this reason, the effect of altitude on these contact conditions could not be determined.

INTRODUCTION

The manner in which airplanes are landed in routine operations is of primary concern in setting limitations on the operation of airplanes on existing runways, in the design of new runways, in the design of airplanes themselves, and to some extent in the overall safety of flight operations. The National Aeronautics and Space Administration has been obtaining statistical data on the landing contact conditions of land-based aircraft during routine daytime operations for both military-type and present-day transport airplanes. Results for the transport airplanes (all propeller driven) are presented in reference 1. Results for military-type airplanes, which include some jet-propelled types, are presented in references 2 to 5. All these published data relate essentially to sea-level airports. A question was raised as to a possible effect of altitude on the contact conditions. Consideration of the lower density at altitude suggested that the contact conditions might be somewhat more severe, on the average, in landings on terrain above sea level. Therefore, a recent investigation was undertaken to obtain comparable measurements at a mile-high airport (Stapleton Airfield, Denver, Colorado) and at a sea-level airport (International Airport, San Francisco, California). Several airlines serve each airport in sufficient volume of the various current transport airplanes to permit a substantial amount of statistical data to be obtained in a relatively short time. About 185 routine operational landings were obtained at Denver and about 670 routine landings at San Francisco.

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APPARATUS AND METHOD

The measurements were made from 35-millimeter photographic records of the landings obtained according to a method described in reference 6. The equipment consists essentially of a constant-speed 35-millimeter motion-picture camera fitted with a telephoto lens of 40-inch focal length supported on a vertical shaft which provides for tracking the airplane only in azimuth. The 40-inch-focal-length lens permits setting up the camera at about 1,000 feet from the runway so that it offers no obstruction to aircraft on the airport proper. Further details of the method used and of the reduction of the data, including formulas to obtain the landing contact conditions of vertical velocity, horizontal velocity, bank angle, and rolling velocity can be obtained from references 1 and 6. Locations of touchdown points to obtain distance down the runway from the threshold were determined from measured azimuth angles and simple triangulation. Airspeeds were determined by adding the component of wind parallel to the runway to the measured horizontal velocity.

RESULTS AND DISCUSSION

The effect of altitude has been examined by comparing a sample of the landing measurements taken at Denver (altitude 5,300 feet) with a comparable sample having the same content with regard to airplane types (selected at random from the landings made at San Francisco (sea level)). Thus, a statistical sample of 170 landings at each airport was obtained for comparison and analysis. Although the content of these 170 landing samples with regard to number of the various airplane types is neither pertinent nor significant as far as the results (effect of altitude) are concerned it is given here as a matter of interest and is as follows: there were 49 Convairs, 34 DC-3's, 43 DC-6's, 33 DC-6B's, and 11 Constellations. About seven different airlines are represented in these 170-landing samples. However, it has been found that there is no difference in the statistics of landing contact conditions for different airlines operating the same type of airplane.

The results showing the effect of altitude on the landing contact conditions are presented in figures 1 to 10 as comparisons of bar graphs and probability curves for the Denver and San Francisco statistical samples for each of the following quantities: vertical velocity, airspeed (expressed as percent above the stall), bank angle, rolling velocity, and touchdown distance from the runway threshold. Values of the means, maximums, and the statistical parameters which established the Pearson type III probability curves are given in table I for all the contact conditions.

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Vertical Velocity

A comparison of the statistical distributions of vertical velocity is shown in figure 1, which indicates the frequency of landings in percent occurring in various intervals of 0.5 ft/sec of vertical velocity. The plot shows a marked difference in the distributions for the two airports, with the highest frequency occurring in the interval from 0 to 0.5 ft/sec at Denver, whereas the highest frequency at San Francisco occurs in the interval from 1.0 to 1.5 ft/sec. This difference in distribution, that is, a larger number of landings at Denver in the lower vertical-velocity intervals, results in a statistically significant lower mean of 0.92 ft/sec for Denver compared with the mean value of 1.27 ft/sec for San Francisco. It thus appears that based on the data obtained at these two airports the effect of altitude is to reduce the severity of the vertical velocity on the average. The distribution indicates that at each airport the maximum vertical velocity occurred in the same interval (3.5 to 4 ft/sec).

The comparison of the probability curves of vertical velocity for these same sets of data (fig. 2) indicate that for the lower values of vertical velocity $\left(\text{up to about } 3\frac{1}{2} \text{ ft/sec}\right)$ the probability is somewhat greater that a given value of vertical velocity will be equaled or exceeded at San Francisco than at Denver, whereas above about $3\frac{1}{2}$ ft/sec the indication is a greater probability that a given vertical velocity will be equaled or exceeded at Denver than at San Francisco. The figure indicates that 1 out of 1,000 landings at either airport will equal or exceed about $4\frac{1}{3}$ ft/sec.

Airspeed

The comparison of the statistical frequency distributions of the airspeed at contact (expressed in percent above the stall) occurring in various intervals 0 to 10, 10 to 20, . . . is shown in figure 3. These distributions for Denver and San Francisco are very similar, with the maximum frequency occurring in the same range 20 to 30 percent above the stalling speed and the mean airspeed being virtually the same (24 and 25 percent above the stall). There was also about the same percentage of landings occurring in the same highest bracket (50 to 60 percent above the stalling speed) for the two airports. It should be pointed out that although the percentages above the stalling speed are about the same, the true airspeeds and the stalling speeds are about 10 percent higher for Denver than for San Francisco because of the relative air densities.

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The probability curves for the airspeed (fig. 4) indicate that 1 5
out of 1,000 landings at either airport will probably equal or exceed 6
60 percent above the stall. 8

Distance to Touchdown Point

Figure 5 shows the comparison of the frequency distributions of the distances down the runway to the touchdown points occurring in various 400-foot intervals (0 to 400, 400 to 800, . . ., 2,400 to 2,800) for the two airports. Both distributions indicate that the maximum frequency (something over 40 percent of the landings) of touchdown points were in the interval from 800 to 1,200 feet. The mean touchdown point was 1,058 feet at San Francisco and 1,151 feet at Denver, a difference of only about 100 feet. This mean touchdown point near the 1,000-foot mark has been the result obtained for all airports and for all airplane types investigated so far, regardless of the lengths of runways, which have varied between about 6,500 feet and about 9,000 feet in length. An analysis of the touchdown points on two parallel runways identified at San Francisco as runway 28L and 28R (6,500 feet and 8,870 feet, respectively) indicated no significant differences in touchdown-point distributions. It consequently appears that, where runway length is more than adequate, some other factor or factors must influence the touchdown point, a natural target for instance, such as runway or taxiway intersections, or possibly a desired turnoff point. The bar graph of figure 5 indicates that 6 percent of the landings at Denver occurred at or beyond the 2,000-foot point (4 percent in the interval from 2,000 to 2,400 feet, and 2 percent in the interval from 2,400 to 2,800 feet) whereas less than 1 percent (actually one landing) of the San Francisco landings occurred at or beyond 2,000 feet (in the interval from 2,000 to 2,400 feet). These facts are also indicated quite graphically in the comparison of the probability curves of touchdown distance (fig. 6), which shows, for example, that whereas 1 out of 1,000 landings at Denver will touch down at or beyond about the 3,000-foot mark, only 1 in about 10,000 landings at San Francisco will probably do so.

It cannot be stated categorically that this marked difference in distances to touchdown points between Denver and San Francisco is due to the effect of altitude alone. One factor which is believed capable of influencing the distance to touchdown of airplanes in routine operations is the amount of head-wind or tail-wind component of the wind velocity parallel to the active runway; that is, higher head-wind velocities would be expected, on the average, to result in shorter touchdown distances compared with touchdown distances for airplanes landing with lower head-wind velocities, with tail winds, or under calm conditions. To verify this hypothesis the Denver and San Francisco landings were analyzed to determine the wind velocity components parallel to the runway. The mean value of head-wind components parallel to the Denver active runways was determined to be 4.6 knots, whereas the corresponding mean value for San Francisco was 9.3 knots, or twice as much. Moreover, 16 percent of the Denver landings were with a tail wind, whereas only 5 percent of the San Francisco landings were made with tail-wind components. The statistical evidence thus substantiates the hypothesis with regard to the effect of wind influencing the distance to touchdown from the runway threshold. However, just how much of this distance-to-touchdown difference is attributable to the wind effect and how much is due to an altitude effect, if any, is not known. Inasmuch as the turnoff point at Denver of 3,400 feet from the runway threshold is virtually the same as those at San Francisco (3,300 feet and 3,600 feet for runways 28L and 28R, respectively) it appears reasonable to conclude that a desired turnoff point in this instance would not be expected to contribute to the statistical difference in touchdown distances.

Rolling Velocity

The comparison of the frequency distributions of rolling velocity for Denver and San Francisco is presented in figures 7(a) and 7(b) for rolling toward the first wheel to touch, and away from the first wheel, respectively. The main difference in rolling-velocity distributions is a greater frequency of Denver landings occurring in the lower interval (0 to 0.5 ft/sec), resulting in a mean value of 0.87 deg/sec for Denver compared to 1.19 deg/sec for San Francisco for rolling toward first wheel (fig. 7(a)), and mean values of 0.86 deg/sec and 0.93 deg/sec for Denver and San Francisco, respectively, for rolling away from first wheel (fig. 7(b)).

The relative percentages of landings rolling toward the first wheel to touch (59 percent and 55 percent for San Francisco and Denver, respectively) and away from the first wheel (41 percent and 45 percent) were about the same for both sets of data. The comparison of the probability curves for rolling toward the first wheel to touch and away from the first wheel (shown as figs. 8(a) and 8(b), respectively), indicates that the differences in the probability values for a given rolling velocity are neither uniform, nor in the same sense between rolling toward and rolling away data. For example, 1 out of 1,000 landings at Denver would be expected to equal or exceed a rolling velocity in the direction of the first wheel to touch (fig. 8(a)) of about $3\frac{1}{2}$ ft/sec with a greater probability (about 1 in 100) for the San Francisco landings to equal or exceed the same value. For rolling away from the first wheel to touch, the probability of 1 out of 1,000 landings equaling or exceeding $3\frac{1}{2}$ deg/sec is for the San Francisco data, whereas the greater probability (about 1 out of 400 is for Denver (fig. 8(b)). It thus appears that there is no clear-cut effect of altitude on the rolling velocity at contact according to these data.

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Bank Angle

The comparison of the frequency distribution of bank angles for Denver and San Francisco is shown in figure 9. The distributions are, in general, similar for the intervals of 0.5° up to 2.5°, with the greatest frequency, about 35 percent of the landings, occurring in the interval 0° to 0.5° for both sets of data. The distributions show less than 1 percent (one landing) at Denver with a bank angle greater than 2.5° which occurred in the interval from 3.0° to 3.5°, whereas about 4 percent of the San Francisco landings were above a bank angle of 2.5° with a maximum of 4°. These few relatively high bank angles for San Francisco landings result in a marked difference in the probability curves shown in figure 10. As was the case with distance down the runway, it is not believed that all this difference is attributable to an altitude effect. Again it is believed that the increased wind velocity at San Francisco is at least partly responsible for the greater probability of San Francisco landings to equal or exceed a given bank angle. It has been found that the gusty wind condition has a substantial effect in increasing the values of vertical velocity, bank angle, and rolling velocity likely to be equaled or exceeded for a given number of landings. (See ref. 1.)

Although none of the landings analyzed herein were made under actual gusty wind conditions according to the definition in reference 7, which was the criteria used for analysis of landings in reference 1, the average winds were higher at San Francisco than at Denver, and in general, gustiness increases with increasing wind velocity. There is thus evidence which suggests that the differences in bank angles between San Francisco and Denver are not entirely due to an altitude effect but may be due, in some measure, to a wind effect.

CONCLUSIONS

An investigation to determine the effect of altitude on the statistical landing contact conditions of commercial transports during routine daytime operations from a comparison of measurements of 170 landings at mile-high Stapleton Airfield, Denver, with a similar statistically homogeneous sample of 170 landings made at sea-level San Francisco International Airport has led to the following conclusions:

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1. The only fairly definite effect due to altitude was on the vertical velocity, and the effect was to reduce the severity, on the average, for landings made at the higher altitude. The mean vertical velocity at the mile-high Stapleton Airfield was 0.92 ft/sec compared with that of 1.27 ft/sec at San Francisco.

2. The airspeeds, expressed in percent above the stall were virtually the same at both airports, with mean values of 24 percent and 25 percent above the stall for Denver and San Francisco, respectively.

3. There were significant differences in the statistics of touchdown distances from the runway threshold, rolling velocities, and bank angles between the Denver and San Francisco landings. Evidence indicated that these differences may have been partially the result of the differences in wind velocity parallel to the runway at the two airports. For this reason, the effect of altitude on these contact conditions could not be determined.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 17, 1959.

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TABLE I.- VALUES OF STATISTICAL PARAMETERS FOR LANDING-CONTACT CONDITIONS

(a) Vertical velocity

Airport	Maximum vertical velocity, ft/sec	Mean vertical velocity, ft/sec	Standard deviation, ft/sec	Coefficient of skewness
Denver	3.6	0.917	0.738	1.162
San Francisco	3.9	1.273	.714	.661

(b) Bank angle

Airport	Maximum bank angle, deg	Mean bank angle, deg	Standard deviation, deg	Coefficient of skewness
Denver	3.4	0.791	0.584	0.930
San Francisco	4.0	.858	.750	1.453

(c) Rolling velocity

Airport	Maximum rolling velocity, deg/sec		Mean rolling velocity, deg/sec		Standard deviation, deg/sec		Coefficient of skewness	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Denver	2.9	2.7	0.872	0.860	0.647	0.687	0.681	0.951
San Francisco	3.3	2.4	1.189	.929	.872	.675	.717	.485

[a]Values for rolling in direction of first wheel to touch.
[b]Values for rolling away from first wheel to touch.

(d) Airspeed, percent above stall

Airport	Maximum airspeed, percent above stall	Mean airspeed, percent above stall	Standard deviation, percent above stall	Coefficient of skewness
Denver	53	25.1	10.20	0.236
San Francisco	55	24.0	11.06	.198

(e) Distance from start of runway

Airport	Maximum distance, ft	Mean distance, ft	Standard deviation, ft	Coefficient of skewness
Denver	2,768	1150.6	463.5	0.906
San Francisco	2,011	1057.6	380.7	.476

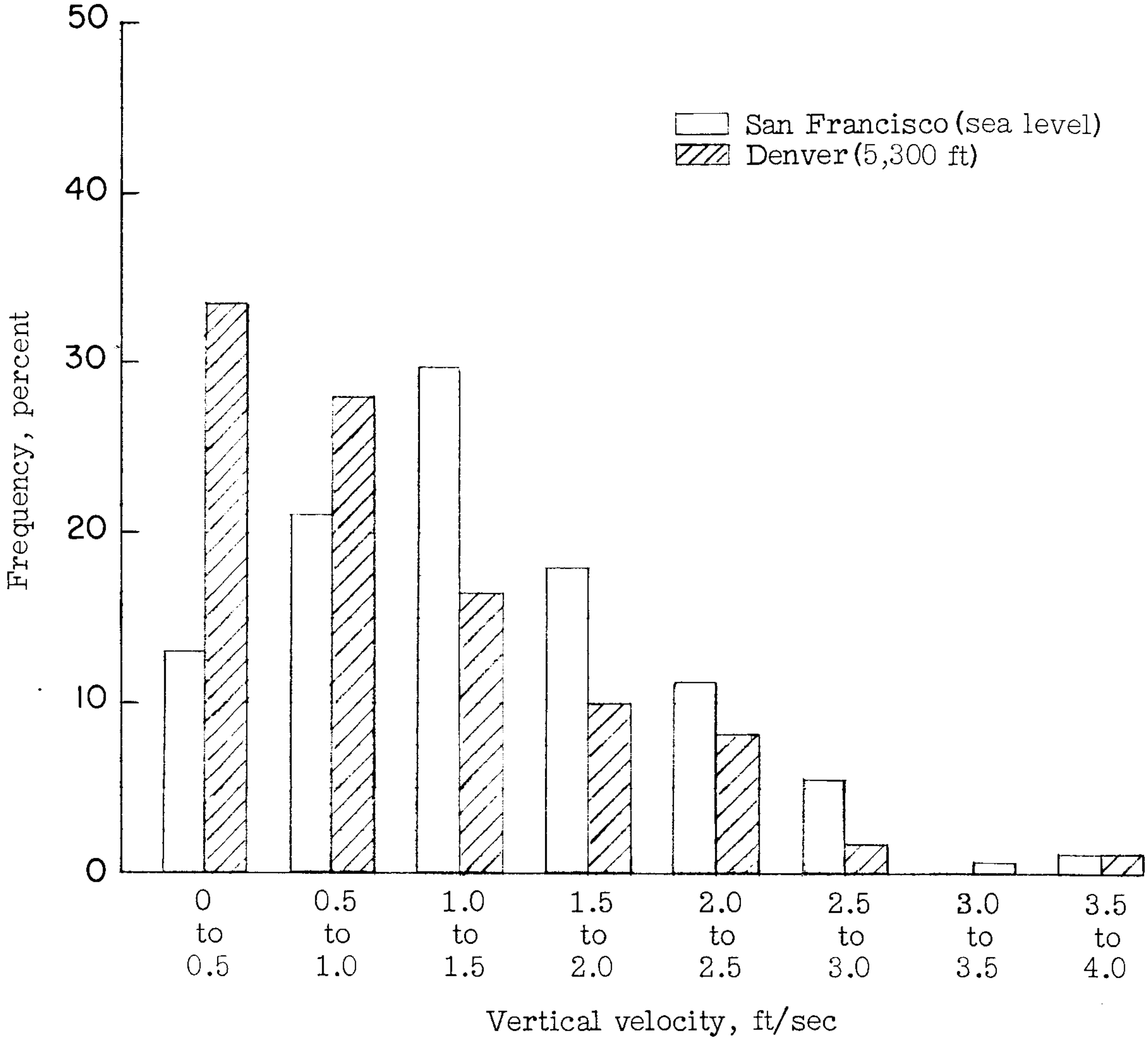

Figure 1.- Comparison of frequency distributions of vertical velocity for 170 landings each at Denver and San Francisco.

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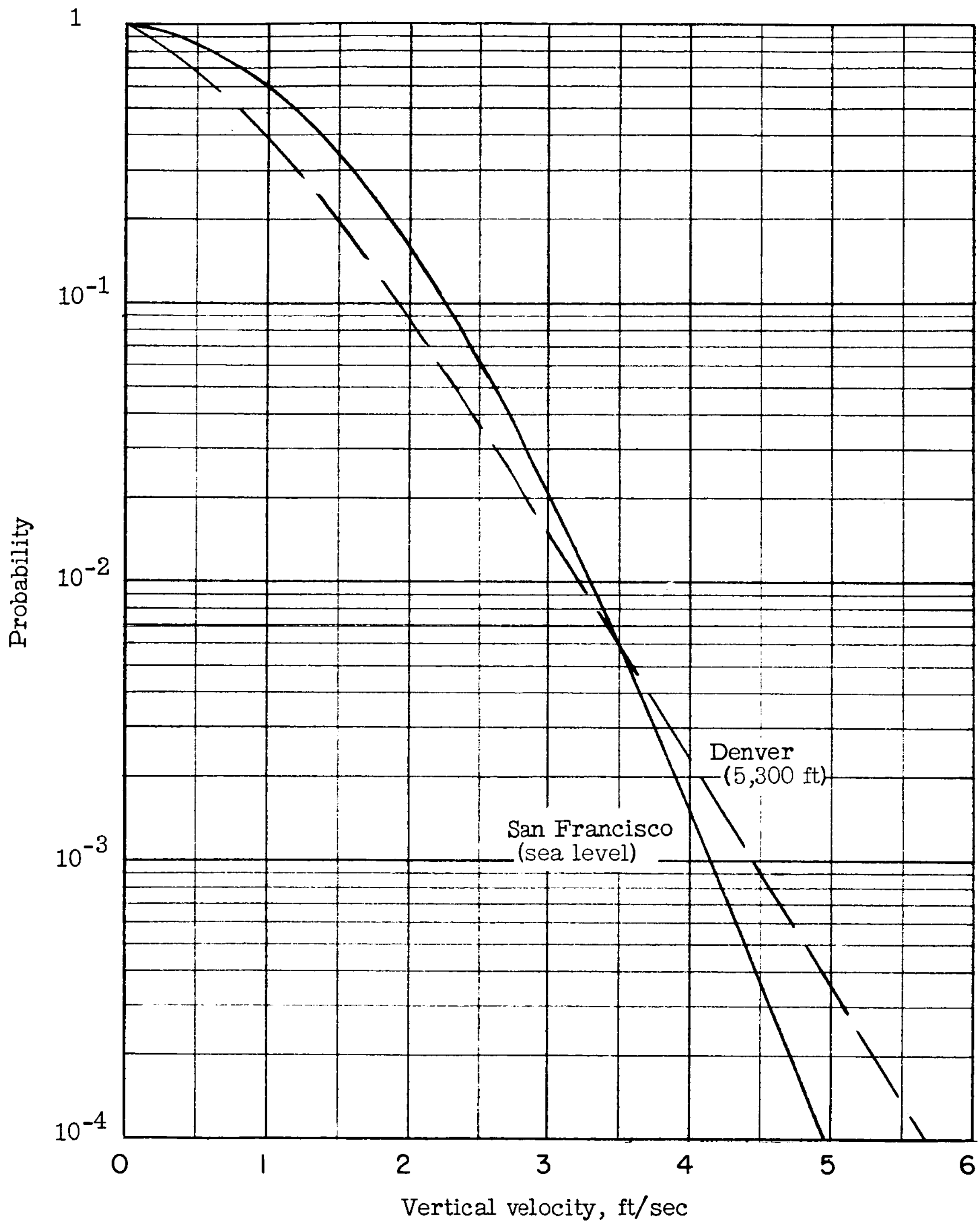

Figure 2.- Comparison of probability curves of vertical velocity for 170 landings each at Denver and San Francisco.

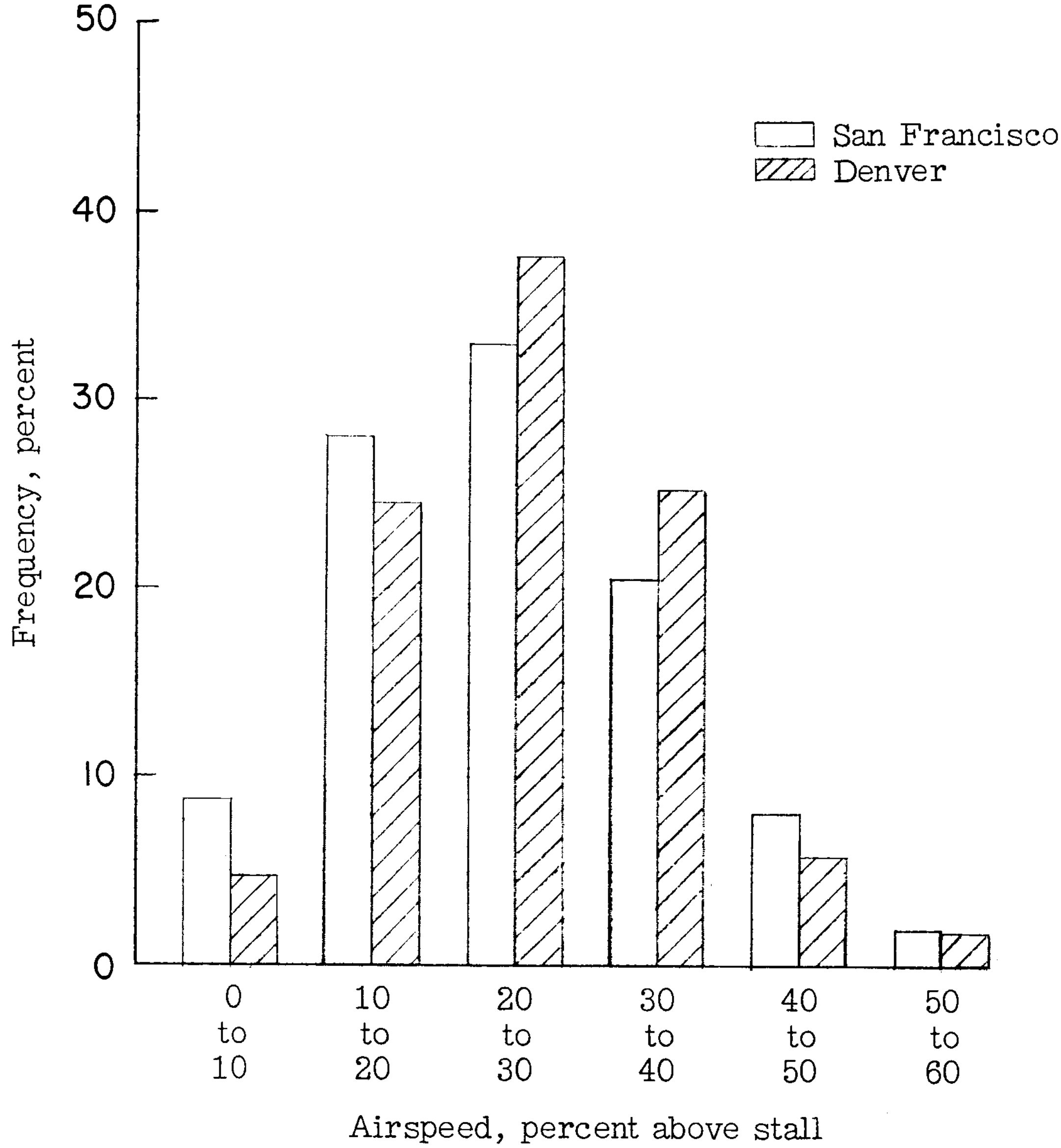

Figure 3.- Comparison of frequency distributions for percentage by which contact airspeed exceeds stalling speed. Stalling speed for condition of 0.9 of maximum permissible landing weight.

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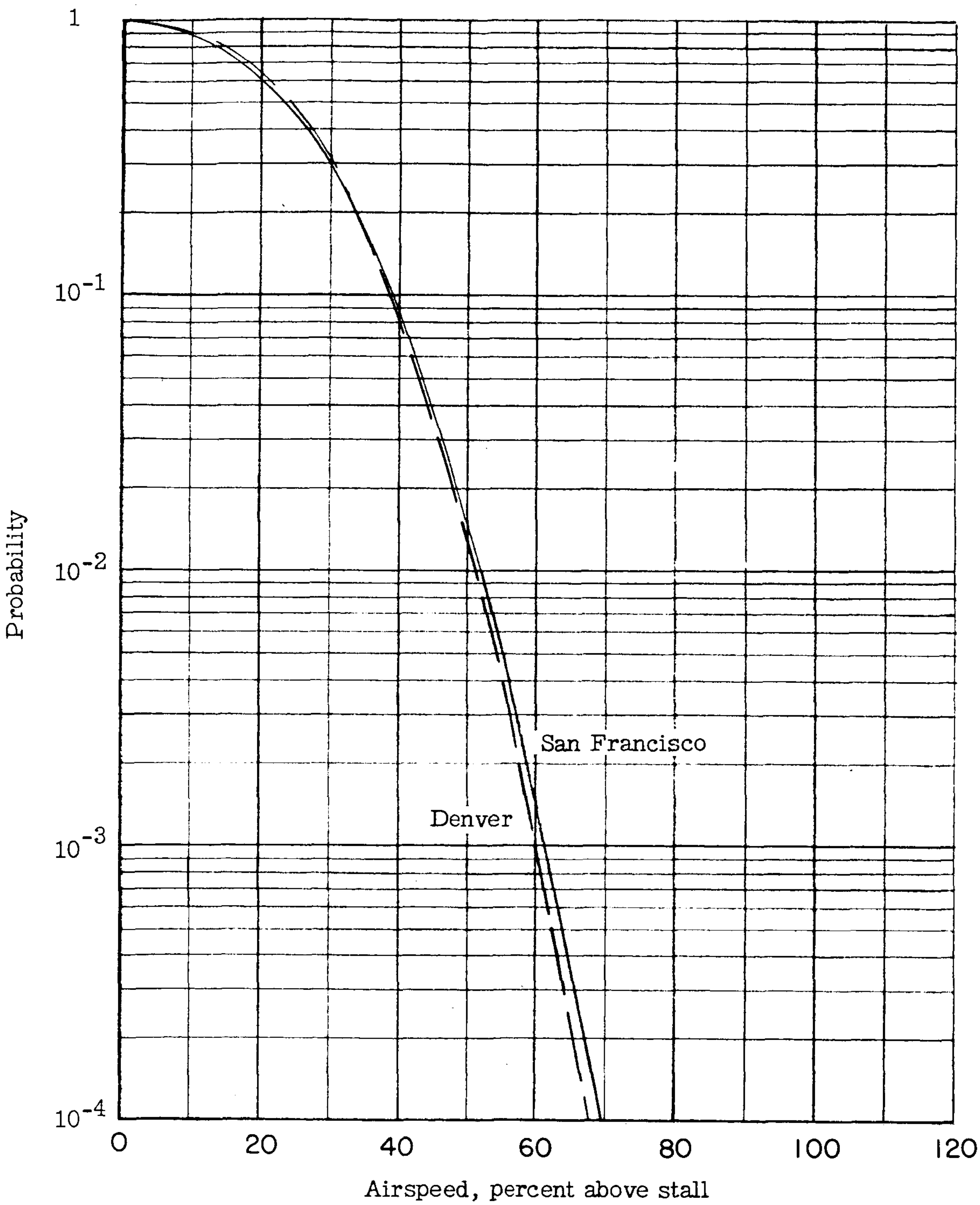

Figure 4.- Comparison of probability curves for percentage by which contact airspeed exceeds stalling speed.

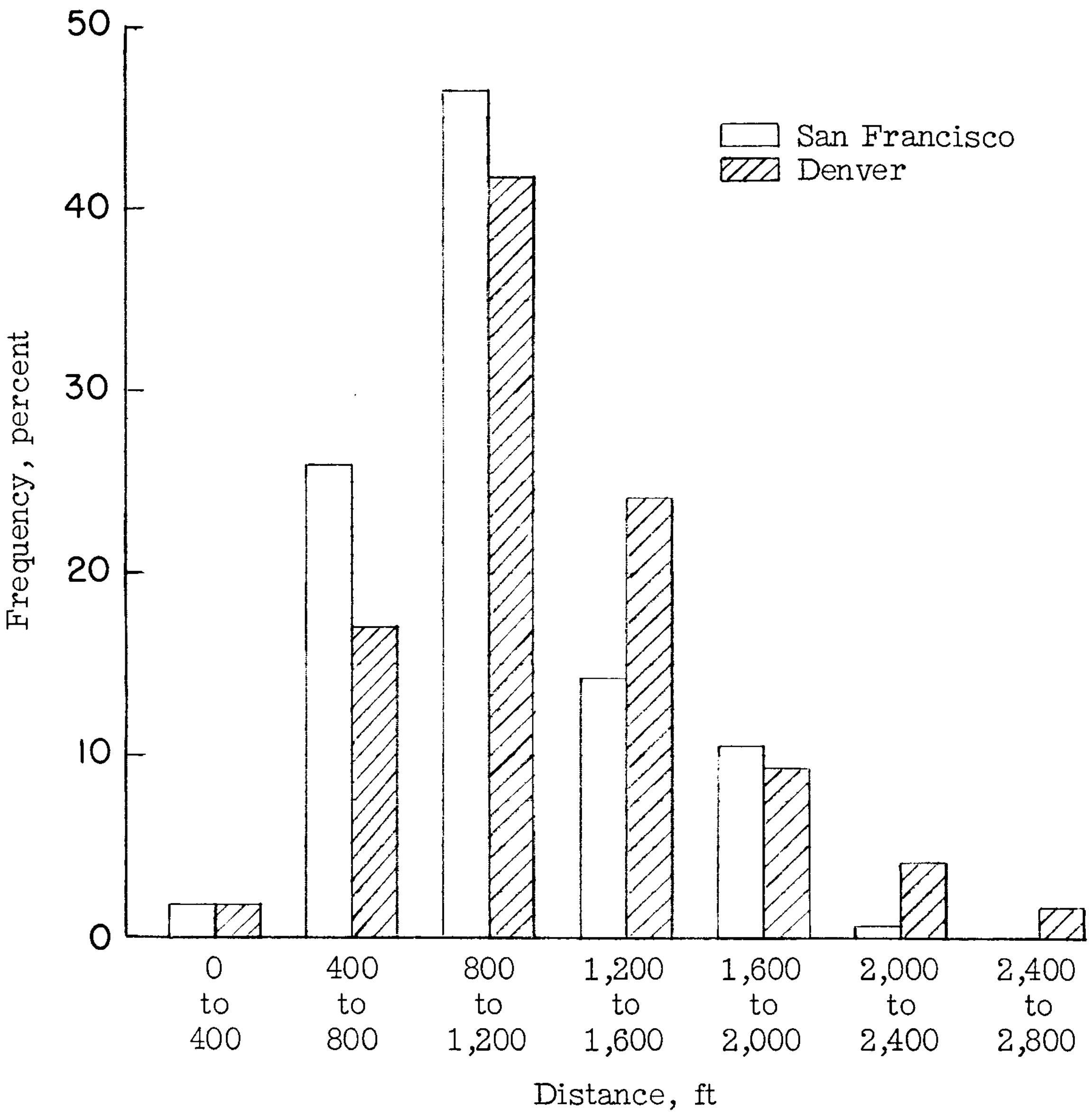

Figure 5.- Comparison of frequency distributions of touchdown distance from runway threshold.

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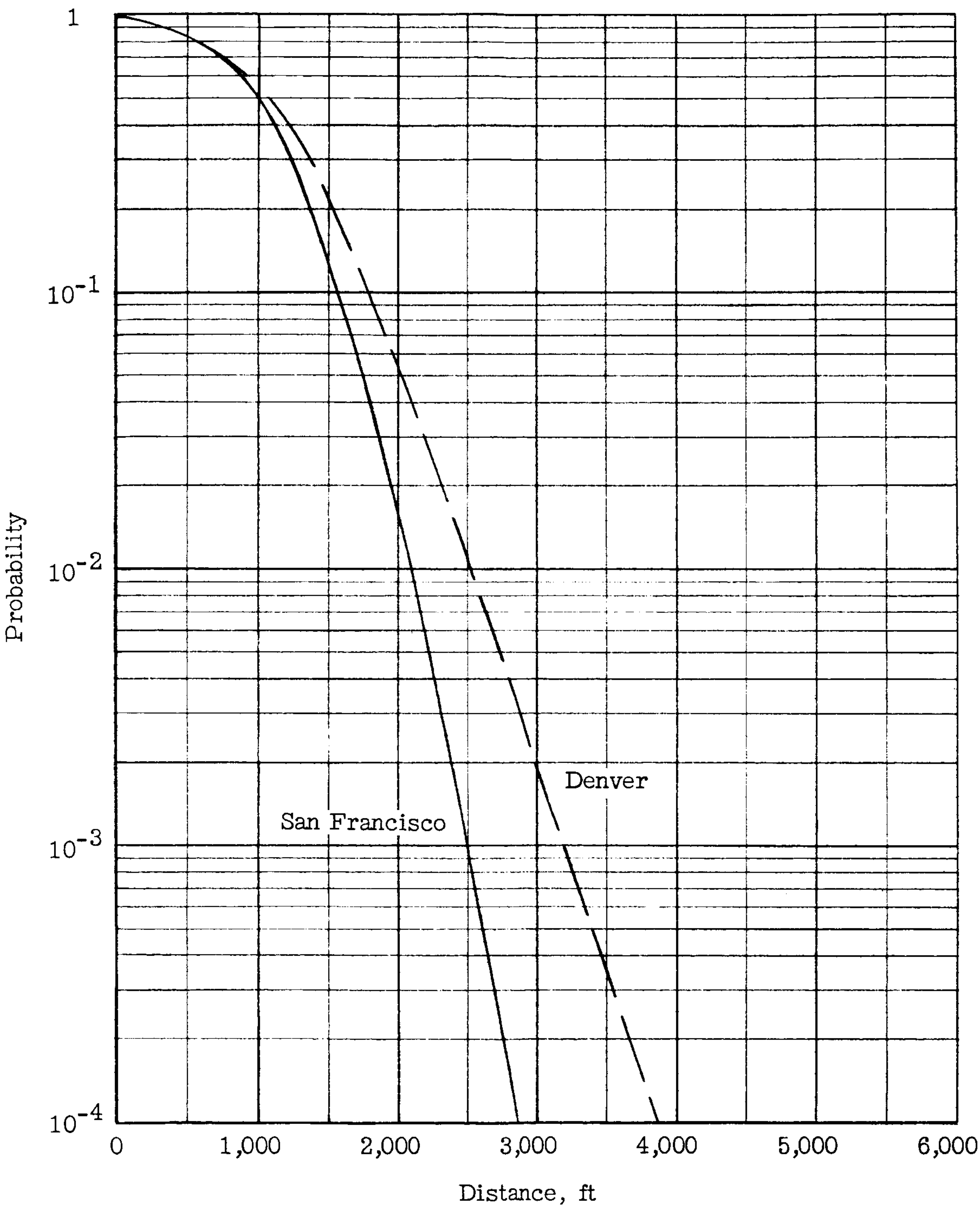
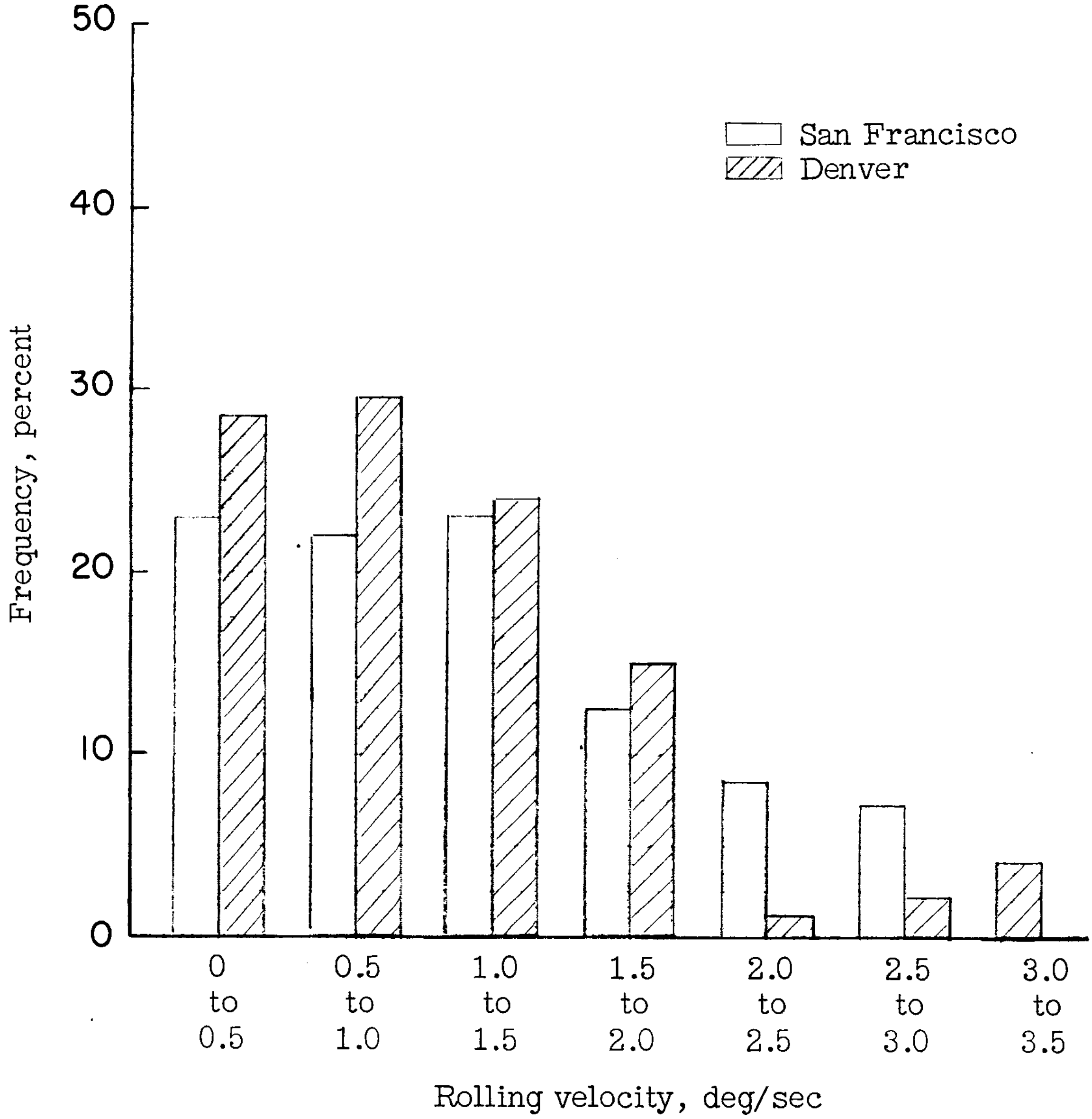


Figure 6.- Comparison of probability curves of touchdown distance from runway threshold.



(a) Rolling in direction of first wheel to touch.

Figure 7.- Comparison of frequency distributions of rolling velocity toward and away from first wheel to touch.

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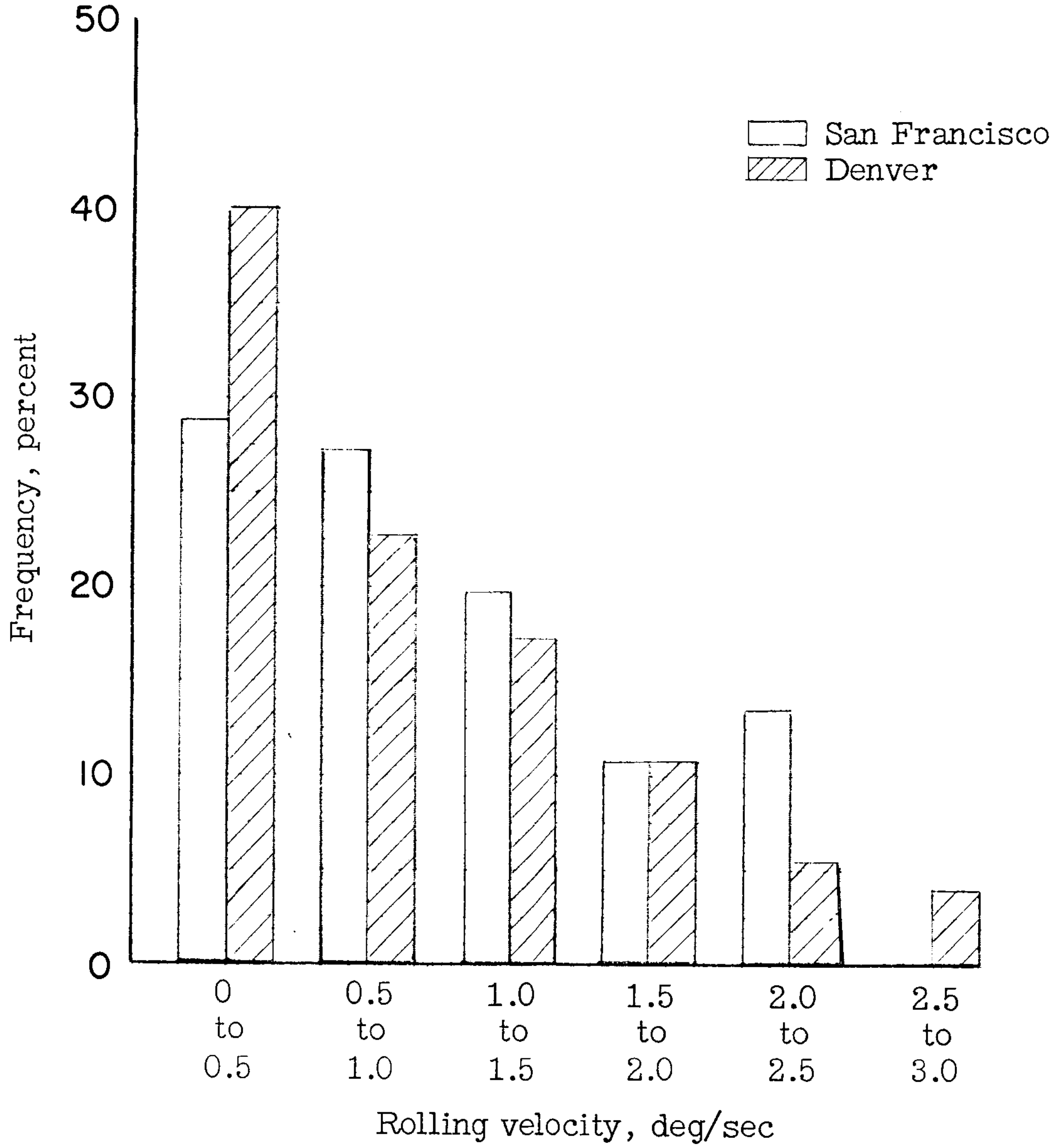
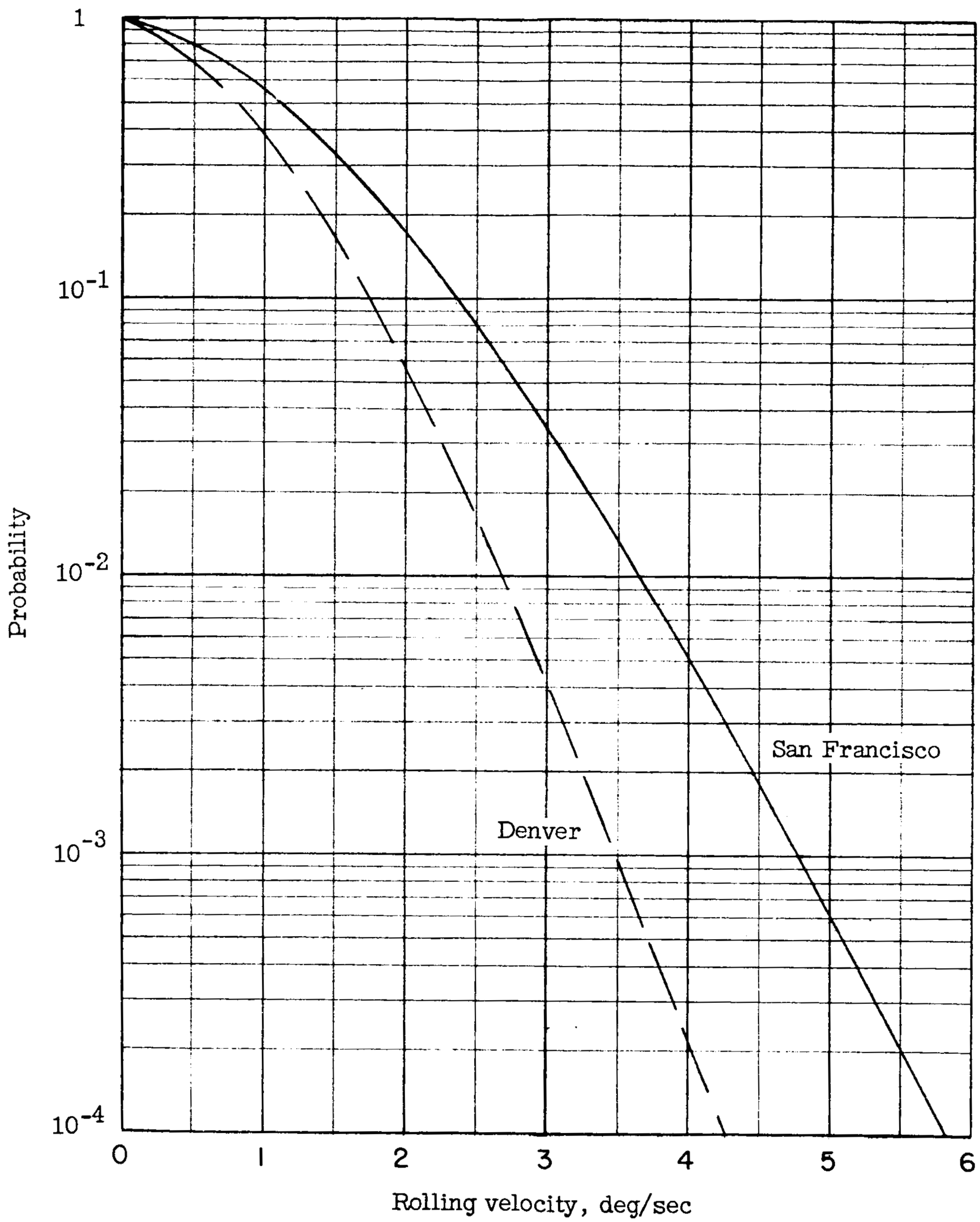


(b) Rolling away from first wheel to touch.

Figure 7.- Concluded.



(a) Rolling in direction of first wheel to touch.

Figure 8.- Comparison of probability curves of rolling velocity toward and away from first wheel to touch.

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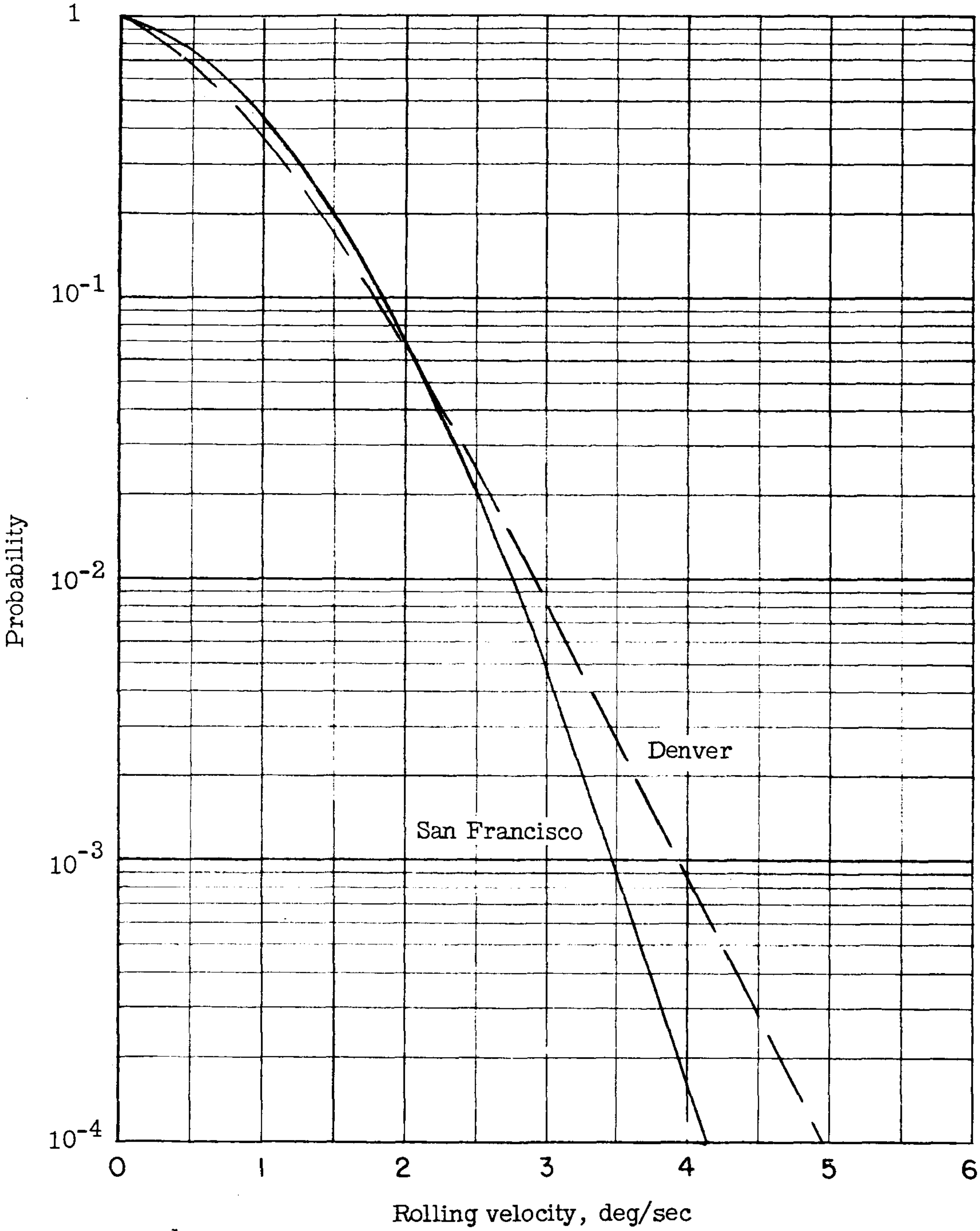

(b) Rolling away from first wheel to touch.

Figure 8.- Concluded.

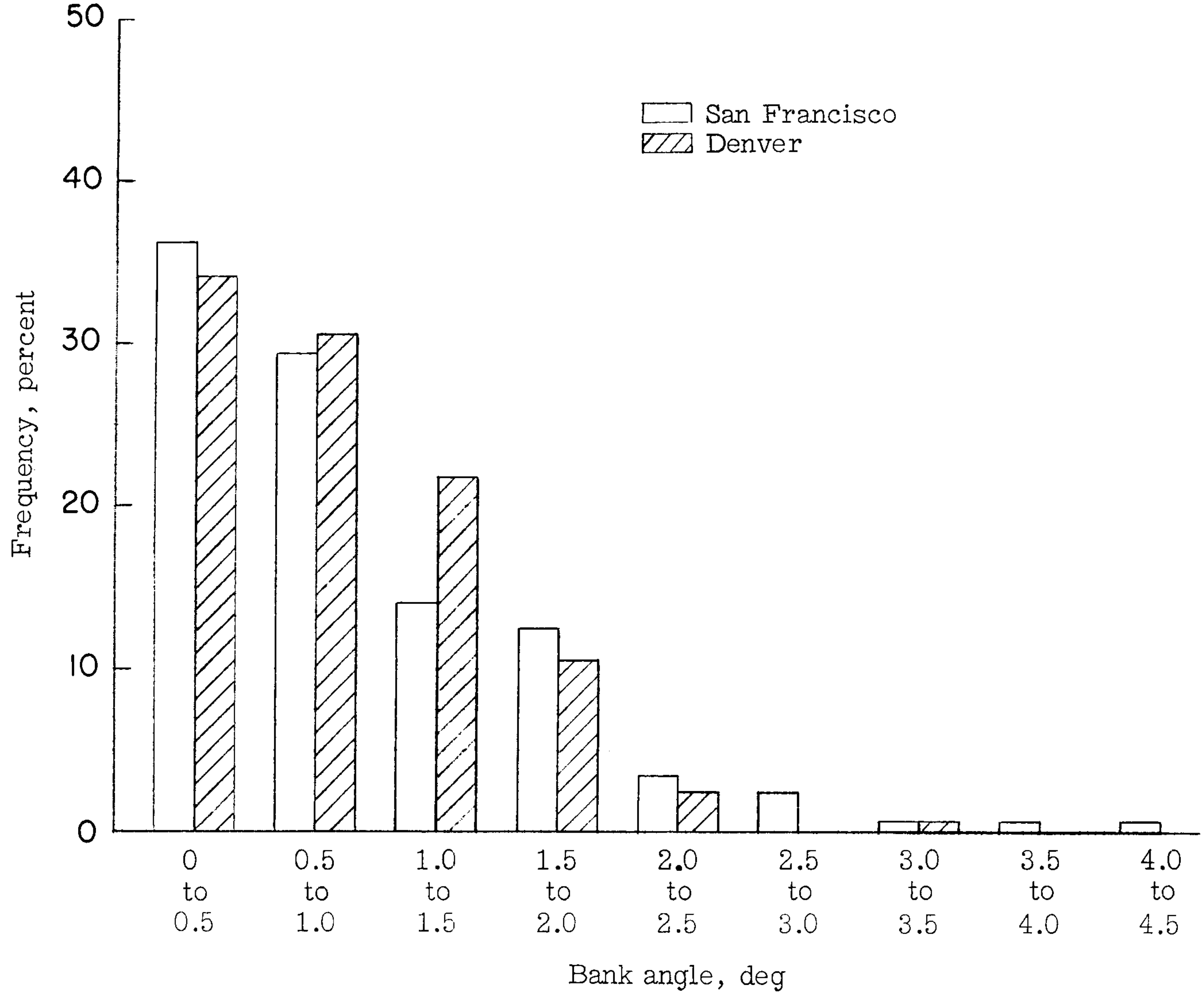

Figure 9.- Comparison of frequency distribution of bank angle.

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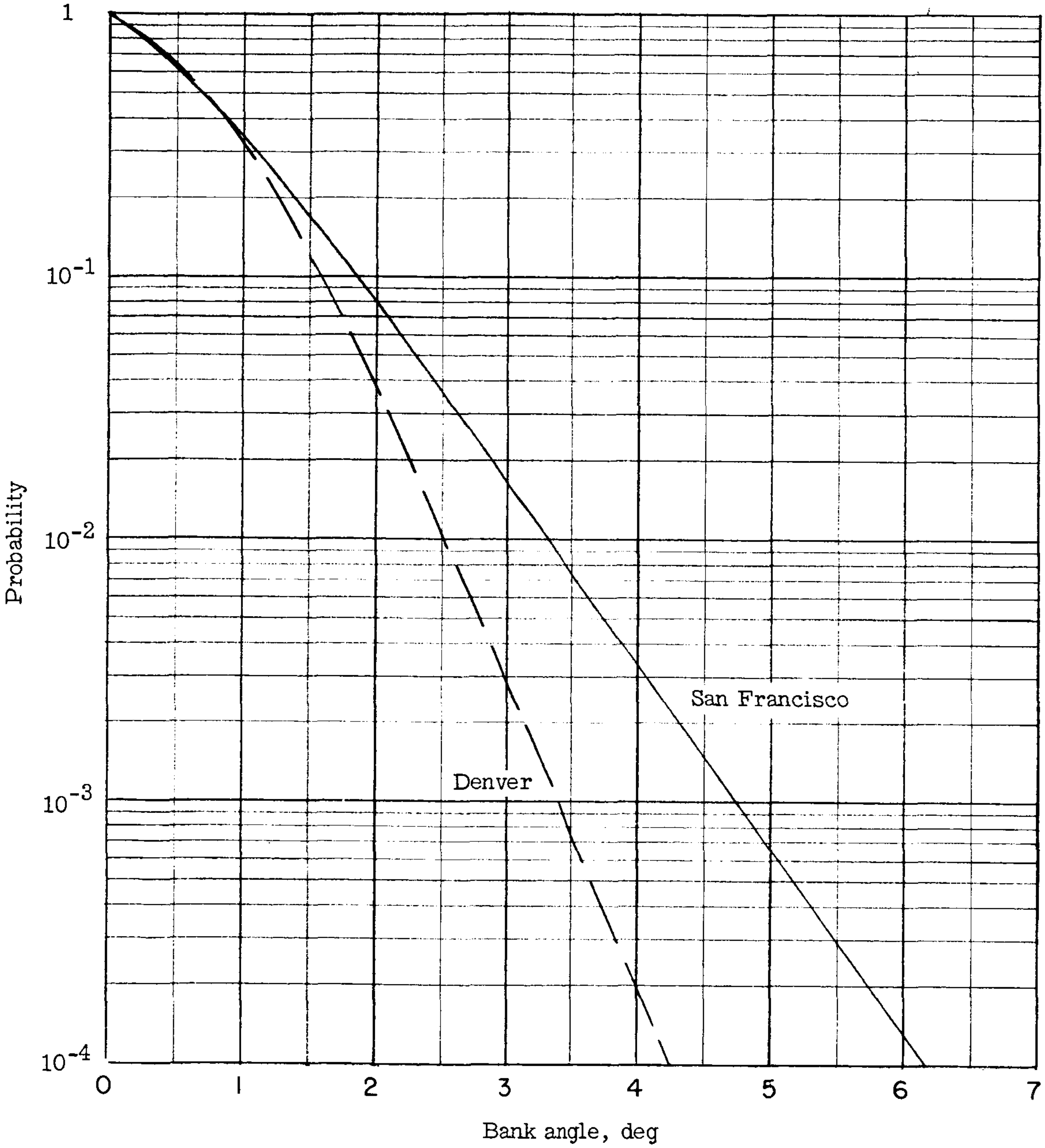

Figure 10.- Comparison of probability curves of bank angle.